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A number of internal and external forces normally act upon the eye, including the intraocular pressure (IOP), eyelid pressure and forces from the eye's internal musculature (e.g. cilliary muscle) and extra-ocular muscles (EOMs). Previous research has shown that changes in some of these forces can lead to alterations in certain ocular optical and biometric parameters. Changes in IOP can lead to alterations in the eye's axial length.[1-3] Changing the position or tension of the eyelids is known to lead to changes in astigmatism and corneal shape.[4-6] Cilliary muscle contraction has also been found to be associated with small but significant increases in the eye's axial length.[7,8]

The forces generated by the eye's EOMs can be substantial, [9,10] and as the global portion of the EOMs inserts into the sclera,[11,12] with the rectus muscles typically inserting within relatively close proximity to the limbus,[13] alterations in EOM forces have the potential to lead to changes in axial length and/or corneal shape. There have been relatively limited studies directly investigating the influence of EOM forces on corneal shape or ocular biometric parameters. Early investigations into the influence of convergence on the cornea, utilizing keratometry or photokeratoscopy were not conclusive, with some studies reporting small changes in corneal curvature with convergence[14,15] and others finding no corneal change.[16] More recently, there have been reports of significant changes in corneal topography following EOM surgical procedures that imply changes in EOM forces may significantly influence corneal shape.[17-19]

Whether altered EOM forces can lead to changes in ocular biometric parameters such as eye length, is of particular interest to research into myopia development, given that near-work is a known risk factor for the development of myopia,[20] and convergence is one of the ocular changes that normally occur when near-work is performed. It has been theorized that the mechanical effects of the EOMs during convergence may be an important factor involved in the axial elongation associated with myopia development,[21] however, there have only been limited studies directly investigating the influence of EOM muscle forces upon ocular biometric parameters such as axial length. Bayramlar et al[22] inferred that convergence may underlie increases in axial length associated with near-work, as they noted significant axial length elongation to occur in young subjects as a result of near fixation, both with and without cycloplegia.[22]

Given the relatively limited amount of research directly investigating the influence of EOMs upon both corneal shape and eye length, we aimed to investigate the influence of sustained convergence upon corneal topography and axial length in a population of young adult subjects.

Subjects and procedures:

Fifteen young adult subjects aged from 20 to 31 years (mean age 26 ± 3 years) participated in this study. Subjects were recruited primarily from the students and staff of our university. Seven of the 15 subjects were female, and all subjects exhibited refractions close to emmetropia (mean best sphere refraction -0.1 D ± 0.6 D range +0.87 to -1.13) normal visual acuity of logMAR 0.00 or better (mean best corrected logMAR VA -0.08 ± 0.09), and no history of strabismus or amblyopia. No subjects had any history of ocular pathology or prior ocular injuries or surgery. Approval from the university human research ethics committee was obtained prior to commencement of the study. All subjects gave written informed consent to participate and were treated in accordance with the declaration of Helsinki.

As the parameters measured in the study are known to undergo some diurnal variation[23,24] and can be influenced by prior visual tasks,[5] testing for all subjects was carried out between 10am and 4pm at least 2 hours after waking, and subjects were advised to refrain from substantial reading prior to the measurements. All subjects underwent an initial screening examination to determine their refractive status and ensure normal ocular health and binocular vision. A series of clinical binocular vision tests were carried out on each subject including: measures of distance heterophoria (maddox rod technique), near heterophoria (Howell-Dwyer card), stereoacuity (TNO test), near point of convergence, and monocular and binocular amplitude of accommodation (push-up method).

Following these initial screening measures, a protocol utilizing base out prismatic spectacles was carried out in order to investigate the influence of sustained convergence upon axial length and corneal topography. All measurements were carried out on each subject's right eye only. All axial length measures were taken using the Zeiss IOLMaster (Zeiss Meditec, Jena, Germany), a non-contact optical biometer based upon the principle of partial coherence interferometry that has previously been shown to provide highly precise measures of axial length.[25] At each measurement session a total of 5 valid axial length measures were collected (i.e. measures with a signal to noise ratio of > 2). Corneal topography measures were carried out using the Medmont E300 videokeratoscope (Medmont Pty Ltd, Victoria, Australia). This instrument is based on the placido disc principle and has been shown to be highly accurate and repeatable.[26,27] At each of the measurement sessions, 4 videokeratoscope measures were captured for each subject. The Medmont E300 provides a score for each measure based upon the focus, centering and movement in the image (from 0-100), and for this study only measures exhibiting scores of 95 or greater were saved. The axial length and corneal topography data were always collected in the same order, with the axial length measured first.

Each subject had their axial length and corneal topography measured immediately before and then immediately after they wore 8 Δ base out prismatic spectacles (in conjunction with their best distance sphero-cylindrical correction) whilst maintaining distance fixation (i.e. viewing a television at a distance of 5 metres) for a period of 15 minutes, and then immediately before and immediately after they wore 16 Δ base out prismatic spectacles with distance viewing for a period of 15 minutes. The magnitude of prism used in this study (8ΔBO and 16 ΔBO) were chosen to represent the approximate angle of convergence for intermediate (i.e. ~ 4.5°) and near tasks (~9°). Previous studies of near work induced corneal and ocular optical changes, typically find the majority of change to have subsided 10-15 minutes following the task.[28,29] Therefore, to ensure that prior visual tasks did not influence our results, prior to the 8ΔBO prism wear, a period of 15 minutes of relaxed distance viewing with no prism was carried out, and in between the post 8ΔBO measures and the pre 16ΔBO measures, a period of 20 minutes of distance viewing with no prism correction was undertaken, to allow any residual effects of the 8Δ BO prism wear to subside. Throughout the duration of prism spectacle wear, subjects were advised to maintain clear single binocular vision, and to report any occurrence of diplopia. As distance viewing was maintained for the prism tasks, the eyes were required to converge with accommodation relaxed in order to maintain clear single vision. Therefore this prismatic spectacle task allowed the effects of convergence to be investigated without being confounded by substantial concomitant accommodation. In order to limit crossover effects between the two tasks, the higher magnitude prism correction was always worn last, along with the 20 minute distance viewing task without convergence demand.

To further examine the potential influence of convergence upon axial length, a subset of eight of the original fifteen subjects returned for additional testing on a separate day. On this second day of testing, a high quality, anti-reflection coated prism of power 17.6 Δ (i.e. 10 ° deviation) (Edmund Optics, Singapore) mounted in a trial frame was utilized. The use of this prism allowed reliable measurements of axial length to be acquired during the convergence task. Prior to testing, we confirmed that the presence of the prism in front of the instrument did not influence the accuracy or repeatability of the axial length measures (no significant difference was found in the measured length of the IOLMaster test eye with and without the prism in place). The procedure carried out on this subset of subjects was as follows. Prior to any measures, each subject observed a 15 minute period of relaxed distance viewing (with no prism) following which, baseline (i.e. pre-convergence) measures of axial length were carried out. Subjects then wore the trial frame with the prism mounted base out in front of the right eye and once subjects attained clear single vision, they continued distance viewing for 60 seconds, and a measurement of axial length was then carried out whilst the subject viewed the instrument's fixation target through the prism (i.e. the measurement was collected through the prism as the subject continued to converge). The subjects then continued to maintain distance fixation for a further 15 minutes, wearing the prismatic spectacles. Following this 15 minutes, another measure of axial length was carried out through the prism spectacles. Following this measurement, subjects removed the prismatic spectacles and a final (post-convergence) measurement of axial length was carried out with no prism in place. This protocol allowed pre- and post- convergence measures, along with measurements of axial length during convergence (after 1 minute and after 15 minutes of convergence) to be carried out. The average standard deviation of change in axial length from the first phase of the study (i.e. the measurements captured immediately after convergence) was ~13 microns; therefore a sample of 8 subjects has 80% power to detect a 19 micron change in axial length, whereas a sample size of 15 would have an 80% power to detect an 14 micron change in axial length.

Data analysis:

The average pre-wear and post-wear axial length measurements for the 8 Δ and 16 Δ BO prism conditions were calculated for each subject. The raw corneal topography data from each measurement session from before and after the 8 Δ and 16 Δ BO prism conditions were also exported from the videokeratoscope and analysed using custom written software. Each of the four corneal refractive power, axial curvature and elevation maps from the pre and post 8Δ and 16Δ BO task measurement sessions were analysed to calculate average maps for each measurement session for each subject.

A range of analyses were carried out on the corneal topography average maps to investigate for significant corneal change associated with the convergence tasks. For each of the average corneal refractive power maps (i.e. the pre- and post- 8 Δ and 16 Δ BO prism maps) the best fitting corneal sphero-cylinder was calculated using the method of Maloney et al[30] for each subject's average map from each measurement session. The best fit corneal sphero-cylinder was then converted into the power vectors M (best sphere), J0 (astigmatism 90/180°) and J45 (astigmatism 45/135°).[31]

Each average corneal axial curvature maps were first converted into axial power (assuming a corneal refractive index of 1.376) and the axial power maps were analysed to calculate the average corneal axial power within 8 equal sized 45° segments. This analysis allowed the average change in axial power following the 8 Δ and 16 Δ BO tasks, to be calculated for the nasal, superior nasal, superior, superior temporal, temporal, inferior-temporal, inferior and inferior nasal corneal regions.

To investigate for changes in higher-order corneal surface shape, the corneal height data was fit with Zernike polynomials using a least squares fitting method.[32] Zernike surface polynomials were fit up to the 8th radial order, and expressed in OSA notation.[33] We have previously found that the 3rd and 4th order Zernike corneal surface polynomials are typically the coefficients exhibiting the highest magnitude in the normal population, therefore our analysis of the corneal surface concentrated on these higher order polynomial terms.[34]

The corneal refractive power, corneal axial power and corneal height analyses were all carried out for both 4 mm and 6 mm analysis diameters. Repeated measures ANOVAs were used to investigate for significant change in axial length and the corneal topography characteristics as a result of the 8 Δ and 6 Δ BO prismatic spectacle wear. Similarly, with the additional data collected on the second day of testing, repeated measures ANOVA was also used to investigate for change in axial length during and following the 15 minutes convergence task.

Results:

The refractive and binocular vision characteristics of the population are presented in Table 1. All subjects were close to emmetropic and exhibited normal binocular vision.

Distance and near heterophoria, near point of convergence, stereoacuity and amplitudes of accommodation for all subjects were within clinically acceptable normal limits for young adult subjects.[35-37]

Figure 1 illustrates the mean axial length before and after the 8Δ BO and 16Δ BO prism tasks. Repeated measures ANOVA revealed no significant change in axial length as a result of the prism spectacle wear ($p=0.957$). The mean change in axial length following 15 minutes wear of 8Δ BO prism was 0.003 ± 0.01 mm, and following 16Δ BO prism was -0.003 ± 0.01 mm. The majority of subjects exhibited axial length changes of less than 10μm following the sustained convergence task.

Inspection of each subject’s corneal axial curvature maps revealed small regions of corneal topographical change for some subjects following the prismatic spectacle wear. The corneal changes typically manifested as horizontal regions of distortion located in the superior and/or inferior peripheral cornea that were usually more prominent following the 16 Δ BO task. Figure 2 illustrates the changes observed in the axial curvature maps before and after the 16Δ BO prism task of a representative subject (subject 13), together with digital images of the subject’s right eye in primary gaze and whilst wearing the 16Δ BO prism. Eight of the 15 subjects exhibited similar regions of corneal change.

Analysis of the corneal refractive power sphero-cylinder revealed some small, but statistically significant changes occurring in corneal astigmatism as a result of the prism task. Table 2 displays the mean pre- and post- task corneal power vectors, and p-values from the repeated measures ANOVA. No significant changes were found in the corneal best sphere M, or astigmatic power vector J45 as a result of the convergence tasks. However, astigmatic power vector J0 was found to exhibit a significant decrease as a result of the prismatic lens wear ($p=0.03$). This is indicative of a small decrease in corneal with the rule astigmatism occurring following the sustained convergence task. Figure 3 displays the mean change in each of the corneal power vectors for the 6 mm diameter analysis as a result of the convergence tasks. It is evident that the most substantial change occurred in astigmatic power vector J0 following the 16Δ BO task. The average corneal sphero-cylinder (6 mm diameter analysis) prior to the 8Δ BO task was 49.11/-0.58 x 170, and following the task was 49.09/-0.58 x 170. The average corneal sphero-cylinder (6 mm diameter analysis) prior to the 16 BO task was 49.13/-0.60 x 170 and following the task was 49.07 -0.53 x 170.

The average corneal axial power in a number of the analysed corneal segments was also found to undergo small but significant change as a result of the convergence tasks. Table 3 and Figure 3 display the average and change observed in corneal axial power within the 8 different corneal segments examined respectively for the 6 mm analysis diameter. Similar trends were observed for the 4 mm diameter analysis. It is evident from Figure 3, that the majority of change in axial power occurred following the 16Δ BO prism task. A small, but significant flattening was evident in the superior-nasal (mean change -0.07 D following the 16 BO task, p = 0.02), superior-temporal (mean change -0.12 D, p= 0.0001) and superior (mean change -0.06 D, p = 0.02) corneal regions following the 16 BO task. The slight steepening observed in the inferior nasal segment following the 16 Δ BO task (mean change +0.05 D, p= 0.1) was not statistically significant at this sample size.

Analysis of the higher-order corneal surface Zernike coefficients, revealed a small but statistically significant change occurring in the vertical coma term (Z_3^{-1}) as a result of the prismatic spectacle wear (p=0.004). The changes observed in vertical coma, are consistent with the significant change observed in the corneal axial power in the superior corneal regions. The remaining 3rd and 4th order Zernike coefficients exhibited smaller magnitudes of change that were not statistically significant. Similar trends were observed for both the 4 mm and 6 mm diameter analyses. Figure 4 illustrates the mean change in the 3rd and 4th order Zernike coefficients following the 8Δ BO and 16 ΔBO prism tasks. As with the axial power and corneal sphero-cylinder data, the largest changes in vertical coma were observed following the 16Δ BO task. For the 6 mm analysis, the magnitude of change in vertical coma (Z_3^{-1}) following the 16Δ BO task represents 23% of the mean baseline magnitude of the coefficient.

The results from the smaller sample of eight subjects who returned for the second day of testing for measurements of axial length before, during and after the 15 minute convergence task are presented in Table 3. Repeated measures ANOVA revealed no significant change in axial length as a result of the convergence task (p=0.65). Pair-wise comparisons with Bonferroni correction revealed no significant difference in axial length between the pre-convergence measures and any of the ‘during-’ or ‘post-’ convergence measurements (p>0.9).

Discussion:

We have investigated the influence of sustained convergence, brought about through the wearing of prismatic spectacles on the eye’s axial length and corneal topography. We found no significant change to occur in the eye’s axial length as a result of these sustained convergence tasks. Our findings suggest that the changes in EOM forces brought about by sustained convergence for 15 minutes are not sufficient to significantly alter eye length. The primary muscles involved in convergence are the horizontal rectus muscles, and the global layer of these muscles are thought to insert into the sclera at a point ~5.5 mm (for the medial rectus) and ~7.0 mm (for the lateral rectus) from the limbus.[13] The relative anterior location of the scleral muscle insertion may therefore mean that alterations in muscle force of the horizontal rectus muscles have relatively limited influence on posterior eye length.

It has been suggested that EOM forces generated during convergence may be involved in the axial elongation of the globe in myopia.[21,38] The lack of change observed both during and immediately following the fifteen minutes of sustained convergence in our current study suggests that the mechanical influence of the EOMs on eye length during convergence is relatively small. However we cannot discount the possibility that larger magnitudes of convergence, or convergence sustained for longer periods of time could potentially lead to changes in eye length. The task involved in our current study involved sustained convergence whilst subjects maintained distance fixation. During reading, subjects typically converge, accommodate and also employ eye movements. Studies of EOM forces have found that the forces generated by saccadic eye movements are substantially greater than those required to maintain the eye in an off-axis position.[9] It is therefore probable that the EOM forces generated during a typical reading task will be different to those induced by the sustained convergence task in our experiment, and the influence of reading eye movements upon eye length may be an area worthy of further investigation.

Previous studies utilizing similar high resolution instruments for axial length measurements (i.e. optical biometry based upon partial coherence interferometry) have noted small (mean reported axial elongation ranged from 5.2 µm to 58µm) but significant increases in the axial length to accompany near viewing in young subjects.[7,8] Our findings would suggest that these previously reported changes in axial length with near viewing are primarily due to ciliary muscle contraction as opposed to any concomitant changes in the EOMs associated with near viewing. However, another study utilizing A scan ultrasonography, also investigated changes in axial length associated with near viewing, and attributed the measured axial elongation with near viewing (mean elongation reported was 180 µm) to the effects of convergence, as elongation was observed both with and without cycloplegia.[22] The changes observed by Bayramlar et al[22] are substantially larger than those found in any subject in our current study during or following sustained convergence activity, and are also larger than the changes in axial length recently reported to accompany accommodation.[8] As Bayramlar et al[22], assessed a larger amount of convergence, it leaves open the possibility that transient axial length changes may occur with higher levels of convergence.

In contrast to our axial length findings, we did find significant corneal topographical changes to occur following the convergence tasks. The changes that we have observed in the corneal topography appear at least in part due to changes in the position of the eyelids relative to the cornea accompanying the convergence task, as illustrated in Figure 2. When the eyes converge the cornea moves relatively nasally with respect to the palpebral fissure, which effectively brings the lids closer to corneal centre. Previous investigations have found similar (although typically larger magnitude) corneal topographical changes to occur as a result of the interaction between the eyelids and the cornea in downward gaze.[5,39] These previous studies have also noted comparable changes in corneal astigmatism (a shift towards ATR astrigmatism) and vertical coma as a result of eyelid forces in downward gaze to what we have observed in our subjects following sustained convergence. The changes that we have observed in the superior cornea are therefore unlikely to be directly related to EOM forces, and are most likely to be due to altered interaction between the eyelids and the cornea associated with convergence. However, the slight steepening found in the nasal cornea that we also observed, may be related to changes in the forces from the horizontal rectus muscles associated with convergence.

The corneal changes that we have found with sustained convergence were statistically significant, but were generally of a relatively small magnitude. This magnitude of change following a 15 minute sustained convergence task is unlikely to substantially influence vision or clinical measures of corneal topography. However, it remains a possibility that larger amounts of convergence, sustained for longer periods of time could lead to larger corneal changes than we have observed. Our findings of significant corneal change following sustained convergence may have implications for longer term changes in corneal shape. It has been established that corneal astigmatism typically shifts from a predominance of with-the-rule (i.e. where the steepest corneal meridian is oriented approximately vertically) in young adult subjects, to a predominance of against-the-rule astigmatism (i.e. where the steepest corneal meridian is oriented approximately horizontally) in older adult subjects.[40-42] The change that we observed in corneal astigmatism following the convergence task was in the direction of less with-the-rule astigmatism in our population of young adult subjects. This leaves open the possibility that corneal changes due to convergence over a long period of time may contribute to the shift towards against-the-rule corneal astigmatism that typically occurs in older adult subjects.

In conclusion, we have found no significant change in eye length to accompany sustained convergence. However, some small, but statistically significant changes were evident in corneal topography following sustained convergence.

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FIGURE LEGENDS:

Figure 1: Mean axial length before and after the 15 minutes of 8 BO and 16 BO prism spectacle wear tasks. Repeated measures ANOVA revealed no significant change in axial length as a result of the prismatic spectacle wear. Error bars represent standard error of the mean.

Figure 2: Corneal axial curvature maps and digital images of the eyes before and after the wearing of 16 BO prismatic spectacles. Note the area of change in the superior corneal region in the post task corneal topography map and that this region corresponds closely to the position of the upper eyelid with respect to the cornea whilst wearing the 16 BO prism.

Figure 3: Mean change in corneal refractive power sphero-cylinder power vectors for the 8Δ BO and 16Δ BO tasks. Data from the 6mm analysis is shown. Repeated measures ANOVA revealed significant effect of task for J0 (Astigmatism 90/180°) only ($p=0.03$). Error bars represent standard error of the mean.

Figure 4: Change in corneal axial power within different corneal zones as a result of the 08Δ BO and 16Δ BO convergence tasks. Inset illustrates the different corneal regions over which the corneal axial power data was averaged (N=Nasal, S-N=Superior Nasal, S = superior, S-T=Superior-temporal, T=Temporal, I-T = Inferior Temporal, I=Inferior, I-N = Inferior Nasal). * Indicates region exhibited significant change as a result of prismatic spectacle wear (repeated measures ANOVA $p<0.05$). Error bars represent the standard error of the mean.

Figure 5: Mean change in higher order corneal zernike surface coefficients as a result of the 8Δ BO and 16Δ BO prismatic spectacle wear. Data for the 6mm analysis illustrated. * indicates coefficient exhibited a significant change as a result of the prismatic spectacle wear (repeated measures ANOVA $p<0.05$). The change in all other coefficients was not statistically significant ($p>0.05$). Error bars represent the standard error of the mean.